Sediment trap sampling in surface waters
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Introduction

Vertical fluxes have been a central theme in the Joint Global Ocean Flux Study, (JGOFS), which relies heavily on fluxes measured with sediment traps. For the legacy of JGOFS and future flux studies, it is important that we understand what traps are measuring. As outlined in this report and in an earlier meeting on sediment trap technology (US GOFs Report no. 10, 1989), calibration schemes indicate that traps moored at depth in the ocean quantify the vertical flux of particulate matter reasonably accurately. However, concerns have been raised about the accuracy of fluxes measured with drifting sediment traps in the upper ocean (see, for example, Buesseler, 1991; Michaels et al., 1994). The measurement in JGOFS of individual compounds such as CO$_2$ has been significantly improved with the establishment of, and adherence to, widely agreed protocols and standards thanks to the efforts of individuals such as Andrew Dickson and others (Dickson & Goyet, 1994). The measurement of particle fluxes, however, has no absolute standards because fluxes are the cumulative result of a series of complex hydrodynamic, biological and chemical processes rather than the precise analysis of a single compound. Carbon fixed into particulate form in the ocean surface can settle by gravity, be removed by vertically migrating organisms, be re-mineralised and mixed downward as DOC or across the air-sea interface as CO$_2$, or advected laterally. JGOFS studies have shown that c. 50–80% of the carbon flux occurs as gravitational settling. Therefore, quantification of the vertical flux and collection of samples of settling material for compositional analyses is of great importance in unravelling biogeochemical cycles, so we must improve our understanding of particle dynamics and settling and the tools used for particle collection.
During the First International JGOFS Symposium in Villefranche-sur-Mer in May 1995, a meeting was held to discuss the status of the use of sediment traps in the upper ocean for collecting and quantifying the flux of particles, especially organic carbon. During the 75 min meeting, we could scarcely do more than enumerate the potential problems in the use of traps in the open ocean. A draft of comments made at the meeting was circulated in August 1995 to the participants and to the invitees who were not able to attend and additional comments were solicited. Additional comments were solicited on a greatly expanded version of the report in November 1995 and posted on the World Wide Web at http://www-ocean.tamu.edu/JGOFS/contents.html. This final version has a few updates and is in a slightly different format from what appeared on the Web.

There is a wide range of possible trap designs and environmental conditions for their use. Protocols for the use of traps have been outlined twice (US GOFs, 1989; Knap et al., 1996), but have not always been followed because of differing opinions and our inability to devise unequivocally accurate calibration schemes that can be routinely followed for surface waters. Thus, we have not progressed to the point of the CO₂ measurements in establishing protocols that are fixed, widely accepted and adhered to.

The objective of this chapter is to assess the present status of particle trapping in the upper water column and suggest plans on how to (1) estimate the magnitude of errors in trap and trap-related measurements, (2) resolve differences in fluxes measured by different methods in the upper 200 m, (3) establish which ancillary measurements are needed in future trapping experiments, and (4) verify which protocols should be used for traps.

To accomplish this objective, we list and discuss some of the potential causes of biases in using traps in surface waters and estimate the magnitude of their importance. We acknowledge disagreement in this assessment because we have not been able to adequately quantify the errors under all conditions. Although many of the issues in this chapter were discussed in the US GOFs Report no. 10 (1989), half of the references in this chapter were published after the GOFs report and they demonstrate substantial progress. This chapter is an update of the major issues with a narrow focus on using and calibrating traps in the upper 200 m of the water column.

**Carbon imbalance and balance**

As a unifying theme, the discussion centres around the potential impact of each parameter on the carbon imbalance reported by Michaels et al. (1994) at the Bermuda Atlantic Time-Series station (BATS), and the carbon balance at the Hawaii time-series station (HOT).
BATS carbon imbalance

At BATS a one-dimensional (vertical) mass balance was constructed for carbon during the April–December period when sediment traps were deeper than the mixed layer depth. The time course of total carbon standing stock (DIC + DOC + POC) was compared with the balance of all vertical fluxes (measured or estimated). The carbon changes in the water were three times greater than the balance of the fluxes. If the discrepancy were entirely due to under-trapping, the traps would have had to collect six times as much material. Alternatively, advection or vertical migration of zooplankton could account for some of the difference. Re-calculation and some new assumptions have reduced the BATS imbalance to a factor of 2.4 (Steinberg et al., 1997).

HOT carbon balance

At HOT, two different 1-D models predict a carbon export from the upper ocean of approximately the same rate as the measured carbon flux in traps (without accounting for sample dissolution) (Emerson et al., 1995; Quay & Anderson, 1996). Not included in this mass balance was an estimate of the carbon flux due to vertical migration of swimmers or the fluxes of DOC. Thus modifications of our sense of trap accuracy to bring the trap estimate more towards addressing the imbalance at BATS might create a disagreement between carbon fluxes and model estimates at HOT.

In constructing a carbon balance, we must remember that carbon can be removed from surface waters by several processes; gravitational settling of particles, vertical migration of zooplankton, vertical mixing of DOC, DIC and POC, advective transport that creates a horizontal gradient, and gas exchange of CO₂ with the atmosphere. Traps are intended to collect only the settling particles. Sources of errors in trap measurements include; swimmers, solubilisation of carbon within the trap, and hydrodynamic effects that include trap geometry, flow, wave-induced trap motion, tilt, and the effects of brine inside the trap.

The central question is whether differences in carbon budgets arise because we do not understand the behavior of the instruments we are using (traps and in situ filtration systems) or because we do not understand the dynamics of the system (particle fluxes and dynamics in surface waters, radionuclide distributions and interactions with a wide range of particle types, spatial scales, etc.) or both.

For each issue presented there is a general discussion composed of comments made at the meeting or in response to the draft report, notes on the magnitude of the problem, effect on the balance or imbalance at the HOT and BATS sites and recommendations of what to do in the future. In addition to normal
citations, names in parentheses indicate the person responsible for the comment.

Possible trap biases

Swimmers

Comments

Live organisms may swim or be swept into a trap and eat material collected, or die in the trap and contribute carbon to the sample. Protocols for picking swimmers have been established (Knap et al., 1996), but keep in mind that some swimmers may be part of the vertical flux (Silver et al., 1984). It would be preferable to have a swimmer-avoidance trap. Coale (1990) and Hansell & Newton (1994) have designed traps to separate active swimmers from passively settling material, but neither design is widely used. Peterson et al. (1993) designed a novel cylinder–cone trap with an indented rotating sphere (IRS) separating upper and lower trap segments. The device is designed to eliminate swimmers from lower regions of the trap and to isolate the sample. On average, the flux of material of diameter greater than 850 μm was reduced by 88% relative to identical control traps without the sphere. At the same time, the flux of material smaller than 850 μm decreased to 59–97% (mean 84%) of the flux in identically-shaped control traps without spheres. The C:N ratio of material in the IRS traps was about 10, whereas it was about 8 in the control traps, suggesting some differentiation in the type of material passing around the sphere. During the JGOFS EqPac programme the IRS traps collected much less material than the cylindrical traps of Murray et al. (1996) when they were surface tethered, but the moored IRS trap fluxes were more similar to the fluxes measured with other moored traps (Cindy Lee, personal communication).

In the Mediterranean, pteropods are regularly and abundantly found in the traps (Miquel et al., 1994). In principle, shells with the animal inside do not belong to the trap flux whereas empty shells do contribute to the passive vertical flux (see Harbison & Gilmer, 1986).

Magnitude of the problem

The swimmer problem decreases with depth (Lee et al., 1988; US Gofs, 1989). Even after manual removal of zooplankton under a strong dissecting microscope, much of the remaining carbon in very shallow traps is still swimmer or swimmer-derived particles (Michaels et al., 1990). However, the problem decreases rapidly below 200 m. Karl & Knap (1989) attempted to circumvent the swimmer problem by using combinations of screened and unscreened traps to calculate a swimmer-free flux. A preliminary comparison of
picking methods between HOT and BATS found a 50–100% difference in total carbon. The screening technique used at HOT was employed on replicates of the BATS traps and the resulting carbon estimate with the HOT technique was higher than that with the traditional BATS technique.

**Effect on BATS/HOT carbon imbalance/balance**
Swimmer errors in poisoned traps usually bias traps towards higher fluxes. If more swimmers were picked, trap fluxes would be even lower and the BATS imbalance larger (Tony Michaels). However, removing swimmers also removes attached non-swimmer mass and so tends to under-estimate true fluxes. There is a crossover point somewhere: no swimmer removal over-estimates flux, complete swimmer removal and the attached particles under-estimates flux. The ‘null’ point will vary with size spectrum and, perhaps, species present (D. M. Karl). If HOT traps were processed like BATS traps, the flux estimate would probably be somewhat lower, creating a difference with the modelled fluxes (Tony Michaels).

If traps contain poison, it is not likely that swimmers will eat and leave (Gardner et al., 1983). However, Lee et al. (1987) found a 43% loss of carbon in unpoisoned traps at 3 m in a shallow lake and attributed the loss to zooplankton feeding in the traps. The loss was only 1–3% at 8–10 m depth.

**Recommendations**
It is recommended that all investigators report how swimmers were removed and quantify their abundance. Inter-comparisons of swimmer removal techniques should be done.

**Solubilisation of particulate matter in the trap**

**Comments**
Organic carbon is lost with time (Lee & Cronin, 1982; Gardner et al., 1983; Knauer et al., 1984; Lee et al., 1992), but decay components can be retained in the brine. Knauer et al. (1984) argued that the quantification of these components (e.g. phosphate) could be used to estimate carbon loss. Dennis Hansell pointed out, however, that this is true only if the decay products are unique to the sinking particles. If these decay products are also found in herniating swimmers, then the source cannot be identified uniquely. One would also have to know the percentage of DOC release per unit FOC from swimmers and sinking particles.

Peterson & Dam (1990) demonstrated that the addition of brine to a trap will cause zooplankton to herniate. Hansell & Newton (1994) found a ten-fold difference in DOM accumulation between brined and brine-free trap solutions, which they attributed to herniation of swimmers. In deployments of a
swimmer-segregating trap (1.7 d), the quantity of DOC released caused only a 7% decrease in the total POC flux compared with standard PITS traps (Hansell & Newton, 1994).

C. Lee et al. (unpublished data) measured DOC in their EqPac IRS traps that have reduced swimmer content. It appeared to make up 10–20% of the C flux. This may still be a problem, but probably more for those interested in specific organic compounds.

Measurements of DOC and DIC in sediment traps obviously have not found a wide acceptance and only very few examples of DOC measurements have been published (Hansell & Newton, 1994). DIC measurements in sediment trap samples have not been carried out or published at all to our knowledge. Wolfgang Koeve pointed out that, besides the additional work burden, theoretical considerations restrict the completeness of any DOC + DIC correction of POC flux measurements. Degradation of POC to DIC in sediment traps would increase the $\rho_{\text{CO}_2}$. This increase would give rise to loss of DIC from the sample before the DIC analysis. Excess DIC (above ambient values) would thus be a minimum estimate of carbon lost from the POC sample to the water of the sediment trap cups. The problem of the origin of this excess DIC (sinking particles vs. swimmers) will be similar to that of excess DOC discussed earlier. For routine measurements of DOC, additional problems arise for those samples poisoned with formaldehyde (the poison most recommended from the JGOFS protocols) (Knap et al., 1996). The DOC introduced by formaldehyde appears to be a very large background signal that will not allow detection of excess DOC at a reliable level.

The ‘Kiel Particle Flux Group’ suggested furthermore that not only should the measurement of DOC and DIC in sediment trap cups be optimised, but one should also be aware of possible dissolution of other components. Excess phosphate has been observed frequently (Bodungen et al., 1991) and should be monitored like other constituents of interest to the respective programme (e.g. trace metals, amino acids, fatty acids). If we believe that excess DIC is a significant source of error for our POC flux estimates, dissolved excess Ca also should be monitored to control our estimates of PIC fluxes. It will depend on the precautions carried out to control or even increase the buffer capacity of the seawater in the sediment trap cups whether or not dissolution of POC to DIC and the subsequent increase of the $\rho_{\text{CO}_2}$ in the sample gives rise to the dissolution of PIC for a given sample. Lee et al. (1992) examined the effects of alternative poisons to buffered formaldehyde, e.g. HgCl$_2$, sodium azide, etc. Furthermore, without monitoring excess Ca in the sediment trap cups one would not be able to decide whether any excess DIC should be added to the POC or PIC flux estimate (Wolfgang Koeve).

Obviously, reliable detection of excess DOC and DIC in sediment trap
samples relies on: (1) improving the swimmer avoidance; (2) using poisons other than formaldehyde; (3) controlling the whole carbonate system in the trap samples; (4) measuring and understanding the artificial losses of dissolved tracers from sediment trap cups; and (5) modelling the loss of DOC, DIC and other related dissolved components from sediment trap cups (Wolfgang Koeve).

Experimental laboratory and field tests carried out showed that losses of dissolved compounds are small for the ‘Kiel Sediment Traps’. Investigation of losses of the supernatant sodium azide concentration, used as poison during these experiments, was carried out in a series of 11 sediment traps (up to 20 samples each) from moorings deployed over recent years in the northeast Atlantic. Deployment period was one year. On average, blank bottles, which were not exposed to the open funnel, showed losses of 7.5% of the initial value of the poison. Higher loss values (up to 20%) occurred in the sample bottles, which were exposed to the funnel for 8–28 d. These higher losses can be explained by reaction of the poison with particles, diffusion, swimmer activity, and probably turbulent mixing events (Lundgreen et al., 1997). This source of uncertainty needs to be evaluated for other sediment trap designs. Because it will be highly dependent on the hydrodynamic environment of the sediment trap for a given experiment or field study, regular measurements are recommended. Tracers other than the poison sodium azide need to be discussed. Kremling et al. (1996) recently used “Na as a tracer in another study.

The VERTEX group found that dense NaCl brines cause CaCO_3 to dissolve (Honjo et al., 1992), so they switched to a NaCl, MgCl_2, CaCl_2, KCl mix in making their brine. Brines also ‘purge’ interstitial fluids of particles that could contain substantial amounts of nutrients (Karl et al., 1984) and biogenic gas (Karl & Tilbrook, 1994).

If C, N, P, etc., are lost owing to herniation of swimmers, maybe we should re-define the whole biogeochemical cycle in terms of Si, which has a much smaller magnitude problem with swimmers. If the carbon imbalance problem finally falls on swimmers, perhaps this is a viable solution, or at least a test of the hypothesis (Dave Karl).

**Magnitude of the problem**

The decay rate is a function of the length of deployment and what poisons and/or preservatives are used. In some earlier VERTEX studies, carbon fluxes were increased by a factor of 2.23 to ‘correct’ for the presumed dissolution in traps (Knauer et al., 1990). This is no longer done (Tony Michaels). Lorenzen et al. (1981) reported a 7% loss per day for 5 d using sediment trap material. Iturriaga (1979) reported an 8% loss per day for zooplankton and a 3% loss per day for phytoplankton in water at 15°C. In the upper water column, carbon
losses were about 4% per day in 1.7 d (Hansell & Newton, 1994). Gardner et al. (1983) measured daily losses of 0.1-1% per day extended over 106 d in deep traps, and showed that if carbon losses were much greater than 1% per day for long-term, multiple-cup trap experiments, seasonal cycles would not be discernible.

Effect on BATS/HOT carbon imbalance/balance
The herniating of swimmers will increase carbon in the supernatant even if they are picked out. Hansell & Newton (1994) found only a 7% difference between total organic carbon and particulate organic carbon after a 1.7 d deployment in Monterey Bay. This is not large enough to solve the carbon imbalance (Tony Michaels).

Recommendations
Several measurements indicate that the carbon loss by solubilisation is at most a few per cent per day in unpoisoned traps. Unless swimmers are prevented from entering the trap, most of any excess DOC signal in trap supernatant water is derived from herniating swimmers. If trap samples are well picked for swimmers, the apparent magnitude of the solubilisation problem appears to be smaller than previously assumed.

Hydrodynamic biases

Comments
One of the major approaches in evaluating the efficiency of sediment traps has been to calibrate small models of traps in flumes or tanks where the conditions of sedimentation can be controlled and measured (Hargrave & Burns, 1979; Gardner, 1980a; Butman, 1986). The experimentally confirmed assumption has been that, in the absence of any current, cylindrical traps accurately intercept the material settling out of the water above the trap. In the presence of velocities up to about 10 cm s⁻¹, cylindrical traps still collect particles at the rate predicted ± 30-50%. The predicted rate is determined from the loss of particles above the trap (Hargrave & Burns, 1979; Gardner, 1980a) or the measured settling velocity of the particles used in the calibration (Butman, 1986). It is difficult to test traps in flumes at velocities much higher than about 10 cm s⁻¹ because settled material is re-suspended from the flume bottom and has a second chance to enter the trap. In flume experiments conducted by Gust et al. (1996), VERTEX-style cylinders showed significant increases in flux between velocities of 5 and 10 cm s⁻¹. However, Gardner et al. (1997) argued that the methods (and therefore the results) of Gust et al. (1996) were flawed because they injected particles into the trap through a tube rather than allowing particles to be intercepted by the trap and collected naturally.
Figure 8.1 Mass flux during two deployments of the moored Flow Actuated Sediment Trap (FAST) decreased sharply (open symbols) when flow increased from less than 12 cm s \(^{-1}\) to 12–30 cm s \(^{-1}\), whereas the mean flux collected simultaneously by a drifting trap in the same area was fairly uniform (closed symbols). (Data from Baker et al., 1988.)

Moving to the field, one continues to make the reasonable assumption that cylindrical traps still accurately intercept the material settling out of the water above the trap if there is no movement past the trap, although independent verification of this assumption would certainly be desirable (see discussion below on independent measures of vertical flux). The effects of large-scale turbulence, internal waves, tilt and mooring-line motions that are not present in the flume have unknown effects on the comparison of flume and field data. Comparisons have been made between cylindrical traps and traps of other designs, such as funnels, that are deployed simultaneously (Honjo et al., 1992). Comparisons of fluxes measured with drifting and moored traps of the same design at the same location can also be used to determine the efficiency of traps under different flow conditions. Baker et al. (1988) have done precisely that experiment.

Baker et al. (1988) showed that relative trap efficiency in moored, cylindrical
traps with a steep inner funnel in the field dropped to 5–25% efficiency somewhere in the velocity range of 12–30 cm s\(^{-1}\) compared with the same design of trap when it was drifting with the water in the same place over the same time (Fig. 8.1). The corresponding trap Reynolds numbers (\(R_t = (velocity \times trap\ diameter)/viscosity\)) for the 20 cm diameter Baker trap were 24,000–60,000. The \(R_t\) or range of \(R_t\) over which the flux decreases is unknown. The composition of particles was also very different at higher Reynolds numbers.

Field experiments by Gardner et al. (1997) showed no decrease in trapping efficiency up to a Reynolds number of 43,000 in cylindrical traps with an interior funnel moored at 4500 m (Fig. 8.2). If Reynolds number were the controlling parameter in trap efficiency, this suggests there should be no decrease in relative trapping efficiency for the 7.6 cm diameter BATS traps up to a velocity of 32–57 cm s\(^{-1}\), which is faster than any of the velocities reported for those traps in the BATS area by Gust et al. (1992, 1994). However, based on personal observations of flow within model traps at just 20 cm s\(^{-1}\), it is hard to believe that the collection efficiency of traps is not affected at velocities above 20 cm s\(^{-1}\) (W. D. Gardner). We must remind ourselves that, although we can scale the dynamics of flow between models and full-scale traps using dimensional analysis, we may not be able to predict the dynamics of natural marine particles within that turbulent flow. Furthermore, in the dynamic region of the upper ocean one must consider whether other factors such as large-scale flow, tilt and mooring dynamics are more important than Reynolds number.

Does the horizontal flux of particles past sediment traps influence the measurement of vertical flux within traps? Measurements by Gardner et al. (1997) of the horizontal flux past moored traps varied by a factor of 56, yet the quantity collected by the traps differed by only a factor of 2.7. Discounting two traps in the benthic boundary layer reduced the variation in apparent vertical flux to a factor of 1.4, and within the 95% confidence interval there is no significant correlation between the vertical and horizontal flux (Fig. 8.2).

Neutrally buoyant traps have been recommended (US GOFS, 1989) and tested (S. Honjo, personal communication, 1980; Diercks & Asper, 1994) but have not been widely used owing to engineering difficulties. Neutrally buoyant traps are not practicable for all environments, but they are well suited to near-surface deployments in the open ocean. Their use could significantly reduce questions about hydrodynamic effects on trapping efficiency. One must also have information about how tightly coupled a neutrally buoyant trap is to the surrounding water. Valdez & Price (1999) have constructed a neutrally buoyant sediment trap based on the RAPOS drifting float design and successfully tested it at BATS. During the periods of low flow and low flux that were tested, there was good agreement between fluxes measured with surface tethered and neutrally buoyant traps, but there were compositional differences
Figure 8.2  (a) Total vertical flux measured by each cylindrical sediment trap versus the horizontal flux past the trap. Numbers are trap identifications. Traps 107 and 110 were in the benthic boundary layer (BBL) and are excluded from the statistics. Error bars are one standard deviation for the vertical and horizontal flux. The heavy line is the least-squares regression of the non-BBL traps. The upper and lower boundaries of the 95% confidence interval of the regression are given by the thin lines and show that statistically, the vertical flux could either increase or decrease with increasing horizontal flux. (b) Total vertical flux collected by each trap versus trap Reynolds number (Re). Error bars are one standard deviation for the vertical flux and Re.
in the material collected (Buesseler et al., 1999). The neutrally buoyant traps contained significantly less swimmer mass. More tests are needed at periods when fluxes and lateral flow are larger. All traps should start with the same minimal amount of brine at the bottom of the trap for a controlled test. A neutrally buoyant trap should minimise the hydrodynamic questions, but leaves the solubilisation and migration transport questions to be quantified simultaneously.


Gust et al. (1992) show a two-fold increase in flux with a doubling of velocity (in the 10–30 cm s\(^{-1}\) range) past large funnel traps during one-day deployments at the BATS site. It is possible that this is more than a velocity effect. Tilted cylinder traps collect more than upright cylinder traps: 25% at 5°, up to 200–250% at 30° (Gardner, 1985). Tilts measured by Gust et al. (1992) were less than 5°, but tilt effects on the efficiency of funnel-shaped traps have not been tested.

A. F. Michaels et al. (unpublished data) have measured velocities at the 150 m trap for nearly 4 years of the BATS programme and, for many of those samples, have looked in detail at the particle composition of the traps. When all the data are considered together, there is no significant trend with velocity (Fig. 8.3). However, if stations of high (over 350 mg C m\(^{-2}\) d\(^{-1}\)) and low (under 350 mg C m\(^{-2}\) d\(^{-1}\)) productivity are considered separately, there is an apparent pattern in collection of carbon with velocity. The collection differences are 2–3-fold higher with increased velocity over the range of approach velocities from 4 to 14 cm s\(^{-1}\). In examining the major components of the carbon flux, there is no velocity pattern with the dominant particle type, marine snow (assuming this can be adequately identified in the trap). There is a strong velocity dependence for faecal pellets (10-fold differences in collection over the velocity range). Thus, the hydrodynamic effects on aggregates may be very different from those on particles that are more solid. Alternatively, faecal pellets in traps could be due to swimmers; swimmer collection might well be a function of approach velocity (and hence the amount of water that passes through the trap mouth).

One area that has received little or no attention is the behaviour and integrity of aggregates in the eddies and flow generated in and around traps. It is also necessary to study how aggregates cross a dense brine interface inside traps. One difficulty in this regard is in being able to identify aggregates once they are collected in a trap. Jannasch et al. (1980) attempted to preserve aggregates by adding a polyacrylamide gel in the sample collection area, so that aggregates
Figure 8.3  Carbon flux (a) and faecal pellet flux (b) in traps at BATS versus apparent velocity at the trap mouth (based on distance/time travelled between deployment and recovery of traps). (Unpublished data from Tony Michaels.)

could be thin-sectioned and studied. However, the viscosity of the gel was so large that aggregates rolled up like dust balls before they sank into the gel (H. W. Jannasch, personal communication, and observation by W. D. Gardner in 1979).

The VERTEX surface-tethered trap array has a stretchable member to dampen out waves. It is important to be sure that there is enough sub-surface
flotation to prevent the stretchable member from ever becoming fully extended or the surface-wave energy and motion will be transmitted to the traps and may affect their efficiency (Vernon Asper, personal communication). Gust et al. (1994) measured significant vertical motion and wave energy on floating arrays of the VERTEX design that had a stretchable member, but it was not reported whether additional flotation was added to compensate for the weight of additional instrumentation on the array.

Vertical motion can be minimised by using a spar buoy as the first or only surface float for drifting traps. An even more effective solution is the VERTEX method of using a string of small floats on the surface, and it is easier to handle. The intent of a spar buoy is to minimise water displacement per unit of vertical displacement or to minimise the waterline area. The string of small floats has a small waterline area and functions like a ‘flexible spar buoy’ (Vernon Asper). The installation of a horizontal drag plate below the trap or at the bottom of the array can act as an effective sea anchor to reduce upward motion of floating traps (Gardner et al., 1985). Most of the drag on a trap array is from the mooring line itself. This can be minimised by using very thin wire (Tony Michaels).

To minimise flow past the trap, position the floats below the Ekman layer to maximise the drag in the vicinity of the traps (Susanne Neuer). Traps at multiple depths make it difficult to minimise the flow past all traps. Deploying one trap per array would improve this dilemma.

Magnitude of the problem

Based on data from Baker et al. (1988), velocity effects could decrease the flux by a factor of 4–5, but potentially only at very high velocities (or Reynolds numbers, \( R \)). Based on unpublished field data there is potentially a 2–3-fold bias at lower velocities (Tony Michaels).

Effect on BATS/HOT carbon imbalance/balance

This could account for the entire imbalance of carbon at BATS, but there is still significant uncertainty about flow effects when floating traps are deployed. If the Reynolds number arguments are relevant in surface waters, then flow effects should be small except at high velocities. The data of A. F. Michaels et al. (unpublished) show a difference of a factor of 2–3 that may be attributed to velocity effects at lower velocities.

Approach velocities are likely to be in the same approximate range at HOT as at BATS based on similar drift patterns, array configurations and horizontal velocities. Thus, any ad hoc explanation for the BATS imbalance that involves a flow-based explanation should have the opposite impact on the comparison of the HOT data with the models at that site.
**Recommendations**

Develop a neutrally buoyant drifting sediment trap (US GOFS, 1989; Diercks & Asper, 1994).

More experiments of the type performed by Baker *et al.* (1988) should be made. The velocity bins need to be more narrowly limited, especially between 12 and 30 cm s\(^{-1}\) (\(R_i = 24,000–60,000\)) because that is where the trapping efficiency decreased markedly in their study. Reynolds numbers should be used when planning experiments and interpreting their results. One should also test funnel traps in this mode: they are one of the most widely used designs because they offer the advantage of large collection area and sample concentration.

Field experiments should be done to compare arrays drogued to have different approach velocities, to see whether there are collection differences in the configuration in which traps are actually used in the field. Although this will only establish a relative accuracy pattern, it will allow a determination of flow impacts in the regime in which these experiments are conducted.

To minimise the flow past the traps, deploy only a single trap per array. Use a buoy or several small floats to remove short-period waves from the array. Use a stretchable segment of mooring line above the trap and be sure it has a rapid response and is never fully extended. Put the maximum drag near the trap depth and use thin lines to minimise the drag at other portions of the array. Measure the velocity past traps on all deployments.

**Effect of adding brine to traps**

**Comments**

Brines with densities greater than that of seawater are often added to traps to isolate samples collected, prevent re-suspension of settled particles, retain poisons and preservatives, and retain dissolved or leached components of the sample. At the BATS and HOT time-series stations, traps are filled to the top with a 50 g l\(^{-1}\) excess brine before deployment. However, one of the important variables controlling trap efficiency is the aspect ratio (Hargrave & Burns, 1979; Gardner, 1980a,b; Bloesch & Burns, 1980; Blomqvist & Kofoed, 1981; Butman *et al.*, 1986). The addition of a brine introduces a hydrodynamic barrier that acts as a false bottom. Thus, brine changes the effective aspect ratio of a trap (the height dimension of the effective aspect ratio applies only to the brine-free region) and also excludes particles or aggregates whose density is less than the brine density.

The density difference between seawater and aggregates in the ocean has been determined to be as low as \(10^{-4}–10^{-5}\) density units (Alldredge & Gotschalk, 1988). Macintyre *et al.* (1995) have observed aggregates accumulating at density gradients in the water column and report that it can take from hundreds of
Figure 8.4  Relative collection efficiency (RCE) of traps during experiments at three different velocities. Collection rates are normalized to the traps with no brine (NB). Samples were wet-sieved at 63 μm. (a) At the lowest water velocity (4.8 cm s⁻¹) the decreased trapping efficiency was largest: nearly 50%; in (b) water velocity was 10.2 cm s⁻¹. (c) At the highest velocity (15.5 cm s⁻¹), filling the trap with brine decreased trapping efficiency by the smallest amount (about 25%).

seconds up to 3 h for the pore water to exchange in the aggregates. Flume experiments show that the addition of a 5 practical salinity units (psu) brine to traps decreased the collection rate (Gardner & Zhang, 1997). The trap efficiency was 54% at 5 cm s⁻¹ and 75% at 15 cm s⁻¹ (Fig. 8.4). Three BATS field
experiments showed carbon fluxes 0, 25% and 60% higher in traps without brine (Fig. 8.5), but showed both increases and decreases in the flux of specific components of the flux (Tony Michaels). Scott Nodder (New Zealand; personal communication) tested cylindrical traps (ID = 9 cm, aspect ratio = 10.6) on frames 3 m above the harbour floor for 24 h filled with a 50 psu excess brine. He found that they collected 2–3 times less material than traps that were partly filled with the same brine (equivalent to 1 or 3 trap diameters of brine). This strongly argues that traps should not be filled with brine.

Tony Michaels argues that a change in any of the protocols at the JGOFS time-series station needs substantial justification that the new measurement will lead to an increase in the absolute accuracy, and it would require an extensive period of simultaneous measurements using both the old and new techniques (e.g. simultaneous brine and no-brine experiments overlapping for a year to test for seasonal differences in hydrography and particle types). Thus, operators of the time-series stations are reluctant to modify one facet of the method (brine) before there is an independent method to determine that the new collection techniques actually result in a flux estimate that is accurate on some absolute standard. It is not considered worth the risk to go through the extensive extra effort of switching one facet to find that the new method without brine is still very inaccurate but for a reason very different from the brine effect (e.g. flow,
large-scale turbulence or something else that is not adequately considered now).

Two groups have discussed this issue (US GOFs, 1989; Knap et al., 1996) and recommended that traps be deployed with no more than a 5 psu excess brine only in the sample-collection region of a trap (equivalent to one trap diameter in cylinders). Trapping programmes should adopt this and the other JGOFS recommendations.

Magnitude of the problem

Flume experiments with a 5 practical salinity units (psu) brine show up to a factor of 2 loss in the flux measured. Field tests with and without a 50 psu brine in cylindrical traps have shown decreases in flux anywhere from 0% to a factor of 2–3. The increases in carbon flux with floating traps in surface waters without brine have been 0–60% higher than with brine-filled traps.

Effect on BATS/HOT carbon imbalance/balance

A brine effect could increase trap fluxes at BATS but the limited brine experiments at the BATS site indicate that the effect would account for about 10% of the carbon imbalance, or 20% of the projected under-trapping. However, experiments in flumes and field experiments at other locations find brine effects of as much as a factor of 2–3. If these experiments are relevant to BATS, they could account for about half of the carbon imbalance, or up to all of the projected under-trapping. The magnitude of the brine effect decreases with increasing velocity and with increased exposure time. The HOT traps use the same protocol and they report no carbon imbalance in their measurements. Any effect of brine on the carbon budget at one site (BATS) must be applied to other sites (e.g. HOT) assuming hydrodynamic conditions are similar.

Recommendations

Follow the published protocols, which call for a 5 psu brine only in the bottom one diameter equivalent of a cylindrical trap.

Make necessary tests to convert the BATS/HOT trap protocols to brine only in the bottom. These comparisons need to be done in the context of experiments to determine the absolute accuracy of sediment traps if they are going to be useful for causing a change in protocols at a time-series station (Tony Michaels).

System dynamics questions

Vertical flux by zooplankton migration

Comments

The role of particle transport by vertically migrating organisms and respiration has been discussed for many years with little quantification because it is a
difficult task (see Angel, 1989). However, traps are not designed to measure the effect of migrant transport. Other methods must be employed to quantify this process. The question of migrant transport does not directly affect the efficiency of traps, but it is an essential component when constructing mass balances in the upper water column for assessing the accuracy of floating traps. One must understand the dynamics of particles and cycling within the upper water column as well as the dynamics of sediment traps.

Migrant transport measured at the BATS site by Longhurst & Harrison (1988) was 8–28% of the carbon flux measured concurrently by floating traps. Recent measurements (Dam et al., 1995) estimated the migrant transport at 18–70% of the trap flux. Walsh et al. (1988) noted a recurring deep (> 1000 m) particle flux maximum in MANOP annual sediment trap profiles. They concluded that as much as 50% of the flux measured in traps at 1500–1900 m bypassed or was produced below their shallower traps at 500–1000 m. This is well below the zone of interest in this discussion, but suggests that migrant transport is not isolated to surface waters. One would expect migrant transport to be largest in surface waters, where diel migration is well documented.

_Effect on BATS/HOT carbon imbalance/balance_

At BATS, the migrant flux of Longhurst & Harrison (1988) was used in the carbon balance (Michaels et al., 1994). A re-calculation of the carbon balance using new migrant flux data decreased the BATS carbon imbalance to a factor of 2.4 (Steinberg et al., 1997). At this site, they noticed that the larger the magnitude of migrant transport, the smaller the carbon imbalance.

Carbon imbalance was not implied by the comparison between the carbon budget and the particle fluxes at HOT, so external transport mechanisms such as migrant transport are not needed to balance carbon budgets. If vertical migrant fluxes occur at HOT, then that system is again out of balance with the carbon budget. Longhurst & Harrison (1988) estimated that migrant fluxes in the oligotrophic Pacific were 0.8–2.5 mg N m⁻² d⁻¹, comparable to an annual carbon flux of 0.2–0.6 mol C m⁻² yr⁻¹. This would increase the HOT annual flux by 22–66%. Is migrant transport less important at HOT than BATS, or are the measurements of migrant transport more likely to be on the low end of the range measured by Dam et al. (1995)? How does migrant transport vary seasonally?

_Recommendation_

The role of migrant transport requires further study, but should be included in an assessment of trap fluxes compared with other independent methods of
Mixed-layer (ML) depth or mixed-layer pumping

Comments
Convective overturning increases the residence time of particles in the mixed layer (Kerr & Kuiper, 1997), so fluxes cannot be accurately measured with traps until you are below the mixed layer (Gardner & Richardson, 1992). Nocturnal increases in the mixed-layer depth (Fig. 8.6) can move particles downward quickly where they are isolated and allowed to settle in non-turbulent flow when the mixed layer thins during the day (Woods & Onken, 1982; Gardner et al., 1995). This is especially important for aggregates, which can rapidly settle below the depth of mixing by the following night and escape re-incorporation into the mixed layer. Conversely, nutrients, $p_{CO_2}$ or any component whose concentration increases with depth in the zone of mixing will be mixed upward. As long as traps are deployed below the mixed layer, this should not affect the fluxes measured with traps.

Effect on BATS/HOT carbon imbalance/balance
Trap fluxes in BATS were examined only when ML depth was less than trap depth, so there should be no direct influence. At HOT the trap depths were always greater than the mixed-layer depths. Total carbon increases with depth, so ML pumping would increase carbon in the surface, not decrease it.
Recommendations
Traps should be deployed below the maximum mixed-layer depth during the time of deployment.

Spatial inhomogeneity

Comments
Particle fluxes have been measured in many parts of the world, but we have little information about the spatial inhomogeneity of vertical fluxes on a scale of kilometres to tens of kilometres. D. Lal suggested deploying multiple traps to test for homogeneity. Time-series traps average out some of the local inhomogeneity depending on length of deployment and advective rates. However, information about spatial homogeneity does not answer the question of accuracy of measured fluxes.

Michaels et al. (1994) analysed the effect of stochastic events on the carbon imbalance problem. Because of the large number of measurements, it is statistically very unlikely that rare, missed events could explain the imbalance at BATS. With the frequency of sampling, there is only a small number of events that could have occurred and not been seen in the BATS sampling. However, these events would have to account for the entire discrepancy and would require an unreasonably large flux (more than the total standing stock of POC every day) to make up for the imbalance. Since the HOT sampling is of similar frequency, the same conclusion can be drawn at that site. The traps at the time-series stations are not grossly inaccurate because they miss rare events.

For a regional study, we may not have enough measurements near BATS to determine whether the error lies in the traps or is a result of large-scale advection. The advective field is not known. Gradients in $^{234}$Th and carbon are small. Do we need to know the 3-D flow field (Tony Michaels)? Are 3-D experiments necessary for every place in which traps are deployed? The question of the role of advection is much larger than the trap accuracy issue and hits to the heart of the interpretation of all JGOFS data (Tony Michaels).

As discussed below in the section on independent measures of vertical flux, mass balances based on oxygen production match the trap carbon fluxes at the HOT site, but not at the BATS site. Perhaps this results from differences in the degree of spatial inhomogeneity of the two sites.

Over what time scales does primary production prevail? Note that trap collections from short-term deployments at multiple depths each reflect the surface production history for different periods (Ian Walsh). Traps at multiple depths may also reflect the flux from different source regions (Siegel et al., 1990).
Magnitude of the problem
Unknown.

Effect on BATS/HOT carbon imbalance/balance
Missing rare events probably cannot explain the annual patterns. Advection may play an important role at each station.

Recommendations
Consider deploying multiple trap arrays to test for homogeneity.
Do control-volume experiments as a follow-on to JGOFS.

Independent measures of vertical flux

Comments
What is the accuracy of the trap measurements? Invoking closure of mass balance cannot be just a convenience when testing for trap accuracy (Tony Michaels). Conservation of mass must be maintained. Closure of mass balances provides validity for other types of calibrations, but the time scales of each measurement must be comparable. Closure should be attempted whenever possible; when observations violate this condition, it is a powerful constraint on the interpretation of data.

When we see disagreements between traps and other measurements, other processes are often invoked as an explanation, but if agreement is seen then the same questions are not raised (Ken Buesseler). This is true of any endeavour in science. We always seek closure of balance and when it is achieved, we move on.

Thorium-modelled and -measured fluxes

Comments
Methodology for this technique is described in Moore et al. (1981), Coale & Bruland (1985, 1987), Eppley & Peterson (1979), Buesseler (1991) and Buesseler et al. (1994). It is based on the fact that $^{238}$U is well mixed in the ocean, is closely correlated with salinity concentrations, and does not react with particles, whereas the daughter product, $^{234}$Th, rapidly adheres to particles and settles out of surface waters with particles. One measures the $^{234}$Th deficiency (relative to $^{238}$U) in surface waters, integrating down to the depth of disequilibrium, which is usually between 70 and 100 m but can extend to 200 m (Fig. 8.7). Obviously, this method is restricted to predicting fluxes to this depth; other studies show that the flux of material decreases rapidly with depth below the upper 50–150 m (VERTEX) or at least that the abundance of particles known to contribute to the vertical flux decreases rapidly with depth (Bishop et
\[ F_{\text{Th}} = \lambda_{\text{Th}} \int_0^Z (U - \text{Th}) \, dz \]

\[ F_C = F_{\text{Th}} \left( \frac{C}{T_{\text{Th}}} \right) \text{ sinking particles} \]

**Figure 8.7** Profiles of \(^{234}\text{Th}\) and \(^{238}\text{U}\) concentrations in surface waters of the Pacific during VERTEX 3 (data from Coale & Bruland, 1987). The \(^{234}\text{Th}\) deficiency is integrated to calculate the flux of \(^{234}\text{Th}\) from the zone of deficiency. The flux of organic carbon is obtained by multiplying the \(^{234}\text{Th}\) flux by the POC: \(^{234}\text{Th}\) ratio for settling particles.

This method may not work along continental margins owing to scavenging and lateral advection and mixing of waters in those regions (Baskaran et al., 1980).

From the \(^{234}\text{Th}\) deficiency, and correcting for the half-life of \(^{234}\text{Th}\) (24 d), one can predict the \(^{234}\text{Th}\) flux (i.e. the loss) over the depth of disequilibrium. Given this and a \(^{234}\text{Th}\) measurement in a trap, one can theoretically make an independent estimate of whether the trap is collecting \(^{234}\text{Th}\)-bearing particles in a predictable (i.e. accurate) fashion. Fortunately, swimmers have low \(^{234}\text{Th}\) concentrations, so their inclusion or exclusion should not affect the measurement (Jim Murray; Buesseler et al., 1994). In an experiment at BATS, Buesseler et al. (1994) predicted a \(^{234}\text{Th}\) flux from 27 water column profiles of
\(-30 \pm 140 \text{ dpm m}^{-2} \text{ d}^{-1}\). However, there was a wide range of both positive and negative values from day to day and over short spatial distances assuming steady-state conditions \((-300 \text{ to } +237 \text{ dpm m}^{-2} \text{ d}^{-1}\)). Buesseler et al. said that the positive values were due either to upwelling of deeper, \(^{234}\text{Th}\)-rich water, which seemed unlikely, or to large errors in \(^{33}\text{Th}\) activity at the low concentrations that result from low fluxes in an oligotrophic area like BATS. Thus, they assumed that the predicted \(^{33}\text{Th}\) flux was essentially zero. Their trap \(^{234}\text{Th}\) fluxes from two arrays during that time was significantly higher \((290 \pm 15 \text{ dpm m}^{-2} \text{ d}^{-1}\)). They explained the difference with a hypothesis that upper ocean traps at BATS may over-collect during low-flux periods and under-collect during high-flux periods based on these data and earlier BATS data. The Buesseler et al. (1994) data demonstrate that multiple profiles are needed in areas of low flux to obtain a statistically meaningful result. More data are needed in areas of higher flux.

Murray et al. (1996) measured the flux of organic carbon from the central equatorial Pacific during EqPac using floating traps at multiple depths and the \(^{34}\text{Th}\) approach described above. In their calculations of \(^{34}\text{Th}\) flux, they included terms to account for upwelling and meridional advection away from the equator. Zonal gradients in \(^{33}\text{Th}\) were found to be small (Buesseler et al., 1995) and were neglected. Comparison of the model \(^{234}\text{Th}\) fluxes with the corrected \(^{34}\text{Th}\) fluxes shows that the model fluxes shallower than 150 m were much less than the trap fluxes. The fluxes at 150 and 200 m agreed to within a factor of \(\pm 2\) from 12°N to 12°S. Murray et al. (1996) argue that all drifting sediment trap studies should be conducted as a function of depth and include \(^{234}\text{Th}\) analyses. The recommendation to have only one trap per depth would require a large number of arrays deployed simultaneously. Error bars also need to be included in reported data, as in Buesseler et al. (1994).

One question about the method concerns the time scales (in terms of minimum and maximum fractions or multiples of half-lives) that are appropriate on which to make \(^{234}\text{Th}\) or other radionuclide measurements. Ken Buesseler responded that if you have only a single radionuclide profile, you need to integrate particle fluxes over a comparable time scale appropriate to the tracer activity. If \(^{234}\text{Th}\) activities are decreasing with time (i.e. particle fluxes are increasing), a single \(^{234}\text{Th}\) profile would actually underestimate the net particle removal at the time you took your sample. If you take a non-steady-state approach (Buesseler et al., 1994) and you measure \(^{33}\text{Th}\) in a time-series (or better yet, 4-D) manner, then you can predict the \(^{234}\text{Th}\) export flux within the measurement period. That is, a period of 2–5 d period is acceptable, as long as you have data to examine whether the \(^{234}\text{Th}\) activity is varying with time during this same period.

The flux of \(^{234}\text{Th}\) will be related to carbon fluxes later; the argument here is
that if the trap is not collecting particles bearing ²³⁴Th in a predictable way, then there is no confidence that they are collecting other particle types in an accurate fashion. However, surface area per unit mass is greatest on the smallest particles, and the small particles are not dominant in the vertical flux of mass. An equally important question is how the adsorption of ²³⁴Th differs between particles of different composition.

Magnitude of the problem

Buesseler (1991) noted that fluxes predicted based on ²³⁴Th-deficiency and trap-measured ²³⁴Th fluxes often disagree by more than a factor of three, with some experiments showing over-trapping and others showing under-trapping by that amount. Time-series measurements of ²³⁴Th deficits were made at BATS during trap deployments (Michaels et al., 1994) and can account for much of the carbon imbalance based on the ²³⁴Th calibration of the traps and the measured range of C/²³⁴Th ratios. Over the course of two years of simultaneous ²³⁴Th profiles and ²³⁴Th collections in traps, both under-trapping and over-trapping have been observed at the BATS site. Their explanation of the variable over- or under-trapping was that their traps over-collected during times of low flux and under-collected during times of high flux at BATS, thus dampening out the seasonal signal of the total flux cycle. Although this may occur at BATS, Rivkin et al. (1997) argued that this is not a global trend.

Effect on BATS/HOT carbon imbalance/balance

The difference between the predicted and measured ²³⁴Th flux is of the same order as the carbon imbalance at BATS (Michaels et al., 1994). If we appeal to advection to account for this ²³⁴Th difference, the magnitude of advection would have to be large based on known gradients of ²³⁴Th concentrations, and there would have to be a seasonal trend to account for the flux imbalance. One might ask why there should be a seasonal trend in ²³⁴Th concentrations in the western North Atlantic. Vernon Asper noted that if the ²³⁴Th deficiency is caused by scavenging and if scavenging is related to the production and flux of particles, how could there not be a seasonal trend in ²³⁴Th concentrations?

²³⁴Th measurements had not been made around HOT until recently (Dunne & Murray, 1997) because the scavenging of ²³⁴Th is generally low in oligotrophic regions, making the ²³⁴Th disequilibrium very small. When scavenging is low, this means that the errors can be large for this calculation (Ken Bruland). Dunne & Murray (1997) found that recycling of POC in the euphotic zone of the equatorial Pacific was 2–10 times faster than at sites previously studied. Their results also suggested that, assuming all particles re-mineralise at the same rate, ²³⁴Th recycled 3–4 times between dissolved and particulate phases before being removed from the euphotic zone on particles. ²³⁴Th deficiency profiles published by Coale & Bruland (1987) in oligotrophic
waters show relationships with mixed layers and zones of particle production that suggest that \(^{234}\text{Th}\) recycling and removal from surface waters is a complex process.

There are times when there is no \(^{234}\text{Th}\) deficiency at BATS, which would imply no particle flux yet the traps collect particles (Buesseler \textit{et al.}, 1994), suggesting we do not fully understand the system or the tools used.

\textit{Recommendation}

See recommendations in following section.

\(^{234}\text{Th}-\text{derived estimates of particulate organic C flux}

\text{Comments}

The \(^{234}\text{Th}\) deficiency method is used to calculate a carbon flux by multiplying the \(^{234}\text{Th}\) flux by the C: \(^{234}\text{Th}\) ratio in sinking particles as determined from trap samples or from \textit{in situ} pump samples. One then compares the carbon flux measured in the trap with the carbon flux predicted based on the preceding calculation. This approach has its own uncertainties, including the time variability and transport terms (Buesseler \textit{et al.}, 1992, 1994; Wei \& Murray, 1992) and the C: \(^{234}\text{Th}\) ratio in sinking particles (Michaels \textit{et al.}, 1994; Buesseler \textit{et al.}, 1995).

To estimate the accuracy of traps at collecting carbon by comparison with the \(^{234}\text{Th}-\text{derived calibration}, however, requires the assumption that the \(^{234}\text{Th}\) is distributed similarly to organic C among the different types of sinking particles, based on composition and settling velocity distribution, that are responsible for the vertical flux of carbon in the ocean. \(^{234}\text{Th}\) adsorption is a function of surface area, and there is much greater surface area per unit mass for small particles that may not be sinking rapidly. How quickly do these small particles become incorporated into larger particles and sink? C: \(^{234}\text{Th}\) ratios vary by particle type and size, but by how much? The biggest concern is the assumption that the particles collected with \textit{in situ} pumps are representative of the local pool of sinking particles. Existing data demonstrate that the C: \(^{234}\text{Th}\) ratio differs between trap and large-volume filtration samples; this result is not surprising since filtration extracts all particles whether they are sinking rapidly or slowly or are neutrally buoyant. The trap–filtration difference during the North Atlantic Bloom Experiment (NABE), however, was as much as a factor of 4 for the same depth and time interval (Table 8.1) and could significantly affect the predicted flux. The C: \(^{234}\text{Th}\) ratio for both traps and \textit{in situ} filters varied by a factor of 2 over 6 weeks in NABE and could vary between seasons (Buesseler \textit{et al.}, 1992). Murray \textit{et al.} (1996) found a very different C: \(^{234}\text{Th}\) ratio during two different cruises across the equator. These changes must be adequately measured and incorporated into the models (Buesseler \textit{et al.}, 1995). \(^{234}\text{Th}\) on fragile, sinking
Table 8.1. Ratio of particulate organic carbon to $^{234}$Th from in situ filtration and from sediment traps deployed at two depths over three time periods in the North Atlantic Bloom Experiment

<table>
<thead>
<tr>
<th>Deployments</th>
<th>Depth (m)</th>
<th>Filter POC: $^{234}$Th (μmol dpm⁻¹)</th>
<th>Trap POC: $^{234}$Th (μmol dpm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>15.0</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>10.6</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>11.8</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>8.0</td>
<td>3.6</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>8.9</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>7.9</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Source: Data from Buessler et al. (1992).

aggregates may break up when they encounter a sediment trap and pieces broken up may not be retained in the trap, or the aggregate may not be able to penetrate the high-density brine used in some traps, thus decreasing the collection of both carbon and $^{234}$Th.

There is an increasing awareness that the POC loss from surface waters due to physical transport and respiration of vertical migrators is important. The physical transport loss is probably included in the upper-ocean $^{234}$Th balance, but the respiration loss is not. Neither portion is likely to be recorded in fluxes measured with sediment traps and this could account for some of the discrepancies between the two methods. Swimmers have low $^{234}$Th relative to POC (Coale, 1990; Buessler et al., 1994), hence the POC: $^{234}$Th ratios in traps may be elevated if swimmers are not adequately removed.

The same concerns expressed above for $^{234}$Th fluxes alone apply here to POC flux, i.e. if the predicted $^{234}$Th flux is incorrect, then the POC fluxes would also be in error (assuming the C: $^{234}$Th ratios have been measured and modelled correctly).

Effect on BATS/HOT carbon imbalance/balance

Using the predicted $^{234}$Th fluxes and measured POC: $^{234}$Th on particles, the $^{234}$Th-derived POC flux would account for up to 80% of the apparent carbon imbalance at BATS (Michaels et al., 1994).

Recommendations

Further studies are essential to examine the range of C: $^{234}$Th ratios in size-sorted sediment trap and size-fractionated filtered particle samples to determine whether the $^{234}$Th-derived trap calibration can be directly applied to POC.
Studies of the U–Th system and $^{234}$Th transfer between dissolved, colloidal, particulate, and aggregate states are also essential, including temporal and spatial variability. However, $^{234}$Th is the most promising independent particle tracer we have. Some feel that any JGOFS trap study should have $^{234}$Th measurements made at the same time (Jim Murray, Buesseler et al., 1994).

In order to validate the $^{234}$Th deficiency method for estimates of carbon fluxes, a trap–$^{234}$Th calibration experiment should be designed and conducted in the highest-productivity, lowest-energy regime (i.e. low advection) that is practicable. Continental margins should be avoided because of the potential for thorium scavenging in the sediments of those regions. This experiment must include explicit consideration of non-steady-state and 3-D effects on the time scale of the experiment (Tony Michaels & Ken Buesseler). Measurements of migrant fluxes should be made simultaneously to account for system processes.

**Oxygen and carbon mass balance**

**Comments**

Spitzer & Jenkins (1989) calculated a carbon flux of $3 \pm 1$ mol C m$^{-2}$ yr$^{-1}$ in the western North Atlantic from an oxygen mass balance model. The carbon flux from floating traps at BATS is only $0.8 \pm 0.2$ mol C m$^{-2}$ yr$^{-1}$ (Michaels et al., 1994), leaving a wide discrepancy between the two methods. Ducklow et al. (1995) calculated that on an annual basis the carbon flux via mixing of DOC equalled or exceeded the POC flux near BATS.

However, the carbon flux calculated from an $O_2$ mass balance model by Emerson et al. (1995) in the HOT area was $1 \pm 0.5$ mol C m$^{-2}$ yr$^{-1}$; the carbon flux from floating traps was $0.9 \pm 0.3$ mol C m$^{-2}$ yr$^{-1}$ (Karl et al., 1996), which is in remarkable agreement. Emerson et al. (1995) also calculated that about 25% of the carbon flux was carried as DOC. The carbon flux calculated from a mass balance of DIC carbon and $^{14}$C-DIC in a 1-D model in the euphotic layer (100 m) by Paul Quay was $1.7 \pm 1.0$ mol C m$^{-2}$ yr$^{-1}$ (personal communication, 1997). This value is larger than the $1 \pm 0.5$ mol C m$^{-2}$ yr$^{-1}$ referred to in Quay & Anderson (1996) because the latter value did not take into account northward Ekman flow in the surface layer. This allows for some discrepancy between the trap measurements and models at HOT, but it is still within the error bars and is much smaller than the discrepancy at BATS.

**Magnitude of error**

The methods show more agreement near Hawaii than Bermuda. However, the comparisons do not include all of the same processes at each of the two sites. Changes in the BATS flux, as a result of a correction for an inferred source of error, tend to have the effect of creating an imbalance at HOT. At BATS there is a difference of a factor of three between trap, $^{234}$Th and carbon budget.
methods (Michaelis et al., 1994), which has revised downwards to a difference of 2.4 (Steinberg et al., 1997). The mass-balance budgets include all vertical processes, but not horizontal advection. At HOT the three methods (trap, oxygen and carbon isotope budgets) agree within the accuracy of the data. They do not include a number of other processes, which may export carbon vertically (DOC, migrant fluxes). The budgets do not include horizontal advection.

One might infer that the agreement at HOT means that traps are accurate at that site. Perhaps there are fewer environmental variables to contend with around Hawaii than Bermuda, e.g. fronts passing the area, winter over-turn, mode-water formation, proximity to a major current such as the Gulf Stream with its attendant rings, and general advection. So there is a better chance of reaching closure for budgets of carbon, oxygen and $^{234}$Th for calibration with trap fluxes. However, it is also possible that the agreement between one form of carbon flux (traps) and the overall 1-D organic carbon budget means that the trap is over-collecting. The current comparison leaves no room for other processes of transport and error such as migrant fluxes, hydrodynamics and solubilisation of carbon.

Recommendations

Continue to make mass balances of this sort where possible whether or not other means of calibration are available. If possible, use multiple independent strategies for comparison with traps.

Comparison with sediment accumulation rates

Comments

Some trap fluxes have matched well with (1) accumulation rate of underlying sediments based on radionuclide dating (Pennington, 1974; Soutar et al., 1977; Dymond et al., 1981; Gardner et al., 1985); (2) accumulation of radionuclides (Moore et al., 1981; Anderson et al., 1983; Bacon et al., 1985; Biscay et al., 1988; Biscay & Anderson, 1994; Colley et al., 1995); (3) accumulation above a known sediment horizon in lakes (Pennington, 1974); and (4) varves (Soutar et al., 1977; Brunskill, 1969 as discussed in Gardner, 1980a; Hay et al., 1990).

It is very difficult to use accumulation rates as a calibration standard of the carbon flux for short-term near-surface traps in the open ocean because so much degradation occurs between the surface and the sea floor. Even in shallow lakes, the time scales can also be orders of magnitude different between trap deployments and accumulation rate measurements (decades for $^{210}$Pb and 100–1000 years for $^{14}$C).

The flux of inert components such as Al can be used as a calibration standard with the assumption that trapping efficiency for POC matches that for aluminosilicates. One must always be aware of the possible ‘contamination’ by
lateral advection of material re-suspended from boundaries, both in traps and in the sediments.

The accumulation of short-lived radionuclides within the water column (e.g. $^{234}$Th) can be measured on time scales close to those of trap deployments.

**Seasonality**

Trap fluxes have been shown to have a seasonal cycle (Deuser & Ross, 1980; Honjo, 1982; Deuser, 1986, 1987). However, a seasonal cycle can exist without one knowing the absolute flux because the entire cycle or parts of the cycle could be biased high or low depending on the dominant particle type or sinking speed and hydrodynamic conditions.

Buesseler et al. (1994) argued that at the BATS site floating traps over-collected during periods of low productivity and under-collected during times of high productivity, thus smoothing out the seasonal cycles, but resulting in an annual average under-collection. Rivkin et al. (1997) re-examined the data of Buesseler (1991) and agreed that there may be a slight under-collection by floating traps, but argued against the hypothesis of over-collection during periods of low productivity and under-collection during periods of high productivity.

**Correlation with ocean colour or chlorophyll**

**Comments**

B. G. Mitchell et al. (in preparation) have compiled floating trap data from numerous projects (RACER, ProMARE, NABE, HOT, CABS, BATS, EqPac) and plotted the fluxes against an algorithm-derived parameter based on sea-surface temperature and a blue: green water-leaving radiance ratio. The 48 points have an $r^2$ fit of 0.71 on a log-log plot. This is comparable to the $r^2$ fit of 0.76 for the same number of points fitting the data of Chl + phaeopigments versus the blue: green water-leaving radiance ratio for the same sites.

Baines et al. (1994) also found good correlations between the amount of chlorophyll in the surface waters and the flux of carbon measured with sediment traps in both lakes and the ocean, although a correlation of the data had a different slope in the two aquatic environments (Fig. 8.8).

One must recognise, however, that there could be a good correlation between flux and any algorithm and still the trap fluxes could all be too high or too low. There is also enough scatter that some of the values could be high or low by factors of 2–3, as seen in the data collated by Buesseler (1991). Care must be exercised in selecting data for this sort of comparison as some of the scatter may result from differences in the depths at which measurements are made, etc.

The important, encouraging point is that there appears to be a real correlation...
Figure 8.8  Sediment trap fluxes of carbon and simultaneous measurements of integrated chlorophyll in lakes (filled circles) and oceans (open circles) (after a compilation by Baines et al., 1984). All data for each study are shown in (a); part (b) averaged all the data in each study. Trends are not obvious in a single study, but the data spanning two decades of fluxes and chlorophyll standing stocks from a variety of environments demonstrate definite correlations.

between chlorophyll or ocean colour and particle flux. Such a relation may seem intuitively obvious to some, but others have questioned whether such a relation could be demonstrated. It is crucial to cover the entire dynamic range of oceanic conditions to establish this relation rather than examining only a small portion of the entire range at one geographic location, in which case the correlation might not be so obvious.

Possible trap errors and their magnitude

Comments
Traps are intended to collect only the particles settling under gravitational forces, not the material carried by vertically migrating organisms or re-mineralised and mixed vertically or advected laterally. It appears that most trap fluxes are within a factor of $\pm 2$ times the true flux, which is actually quite encouraging for a measurement that is the result of so many different biogeochemical and hydrodynamic processes. If trap methodology is not properly adhered to, errors can be larger. Table 8.2 provides a summary of possible errors associated with trap measurements plus system processes that
Table 8.2. Summary of the magnitude of possible errors with traps and the environment

<table>
<thead>
<tr>
<th>Trap errors</th>
<th>Magnitude of error</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Source of error</em></td>
<td></td>
</tr>
<tr>
<td><em>Swimmers</em></td>
<td>Up to 2-fold, depending on techniques</td>
</tr>
<tr>
<td>Solubilisation of carbon</td>
<td></td>
</tr>
<tr>
<td>Poisoned</td>
<td>0.1% to 1% per day</td>
</tr>
<tr>
<td>Unpoisoned</td>
<td>3–7% per day near surface</td>
</tr>
<tr>
<td>Hydrodynamic effects that include</td>
<td></td>
</tr>
<tr>
<td>Trap geometry</td>
<td>Extremes of several-fold for odd-shaped traps</td>
</tr>
<tr>
<td>Flow</td>
<td>Funnel may be 0.7–1.0 × cylinders</td>
</tr>
<tr>
<td>Wave-induced circulation</td>
<td>× 0.2–2 depending on configuration and velocity</td>
</tr>
<tr>
<td>Deployment of traps in the ML</td>
<td>Not quantified</td>
</tr>
<tr>
<td>Tilt</td>
<td>× 1.25–2 for cylinders; not tested for funnels</td>
</tr>
<tr>
<td>Apparent tilt from internal waves</td>
<td>Not quantified</td>
</tr>
<tr>
<td>Effects of brine in the trap</td>
<td>× 1–3 (× 1.6 is maximum seen in surface water)</td>
</tr>
</tbody>
</table>

System dynamics resulting in apparent trap flux errors

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Magnitude of carbon export</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical migration of zooplankton</td>
<td>8–70% of trap flux</td>
</tr>
<tr>
<td>Vertical mixing of DOC, DIC and POC</td>
<td>7–30% in three estimates</td>
</tr>
<tr>
<td>Adveotive transport</td>
<td>Undetermined</td>
</tr>
<tr>
<td>Gas exchange of CO₂ with atmosphere</td>
<td>2% in one estimate</td>
</tr>
</tbody>
</table>

may cause discrepancies between trap fluxes and balances in the carbon budget, and erroneously may be attributed to trap errors.

Summary comments

Sediment traps have opened a new era of investigation of biogeochemical cycles in the ocean. They provided the first proof that seasonal and episodic variations in surface-water productivity could result in variable fluxes at depth in the ocean, thus triggering many new questions to pursue. The collection of samples at various depths has allowed studies of the recycling of oceanic particles and helped to elucidate where many processes are occurring. In turn, this information is extremely important in making comparisons with the small residue of biogenic material that reaches the sea floor, and the even smaller residue that is preserved in the sediments. This is critical to accurately (albeit
very imperfectly) interpret the palaeorecord from sediment cores. It is equally important for understanding correlations on short time scales between remotely sensed ocean colour data from satellites and processes that lead to the export of carbon from surface waters.

Traps have proven to be valuable tools. Particle cycling in the upper ocean is more complex than previously realised. The lack of mass balance in some studies based on trap fluxes is part of what has made us realise that complexity. That does not mean a priori that traps do not (or do) work. We need to make a more concerted effort to fully understand both traps and the particle dynamics in the environments in which they are used. Existing data clearly show that there are trap designs and hydrodynamic regimes in which the results from traps cannot be used in either quantitative (flux) or qualitative (compositional) analyses. On the other hand, there are studies using floating traps where the carbon fluxes match well the macro-scale carbon budgets derived from oxygen budgets determined by completely independent measurements (Emerson et al., 1995; Karl et al., 1996). Other studies show mismatches of as much as a factor of 2.4–3 (Michaels et al., 1994; Steinberg et al., 1997). Further studies are needed to understand why this discrepancy exists.

Standard measurements are needed that can verify or validate trap fluxes. Three basic approaches have been used to calibrate sediment traps. The first has been to calibrate specific trap designs under known conditions in a flume (e.g. velocity, Reynolds number, tilt) and then to use those traps in the field and accept only those data that are collected within physical parameters proven to be acceptable. A variation on this approach is to compare fluxes between a trap moving with the water and one that is not moving with the water to extend the limits of acceptable hydrodynamic conditions. Only a limited number of studies of this type have been made and the hydrographic constraints within which trap fluxes match still-water fluxes must be better defined. The development of neutrally buoyant traps would improve on this method significantly. A second approach is to compare trap fluxes with independent measures of fluxes such as accumulation rates of labile components in the sediments or the loss of a radionuclide from the water column and its accumulation in sediment traps.

$^{234}$Th is the best candidate for surface traps, but there are still some caveats in its use. A third calibration scheme is to develop carbon budgets independent of trap fluxes as a standard for trap carbon fluxes. Comprehensive measurements made in JGOFS and other programmes are making such carbon budgets possible.

Ultimately, one of the prime JGOFS goals is to develop accurate budgets of carbon, carbonate, silica, etc., not to determine a radionuclide flux or trap accuracy. Different environments and seasons have a different portion of material transported by vertical settling versus migrant transport, DOM mixing
or other mechanisms (advection). From that viewpoint, it is a higher priority to
develop a method that can be used to predict the removal of carbon (by all
pathways combined) from the surface water than to determine the absolute
accuracy of traps. However, an accurate calibration of traps would inform us of
the portion carried by gravitational settling. If the $^{234}$Th-deficiency method
could be shown unequivocally to accurately predict the flux of carbon out of
surface waters under all conditions, it would be a very important advancement
for JGOFS. Presently, we assume that traps probably do not collect the material
carried by vertical migrators and they certainly do not collect DOC or
significant colloidal material. Unfortunately, a carbon flux via DOC is not likely
to be apparent in the $^{234}$Th-deficiency method either. Furthermore,
biogeochemical studies require knowledge about more than just carbon cycling,
and trap samples afford the opportunity to examine the composition of settling
material if they are functioning in an unbiased manner. Present JGOFS studies
suggest that c. 50–80% of the carbon flux occurs as settling particles (Carlson et
al., 1994; Gardner, 1997). That is what makes it imperative to calibrate traps.

It is important to remember that comparisons between the trap fluxes and
$^{234}$Th fluxes apply only to the depth over which particle scavenging creates a
$^{234}$Th depletion (the upper 70–150 m or so in the open ocean). Carbon
re-mineralisation is rapid below the euphotic zone, so carbon fluxes decrease
rapidly. Still, a proven calibration scheme for traps in this depth range is
important for comparisons with short-term processes in the euphotic zone and
with satellite data. With regard to long-term sequestration of carbon, fluxes to
the deep ocean and to the sea floor are far more significant than carbon fluxes out
of the upper 200 m. Agreement between longer-lived radionuclides and trap
fluxes at greater depths has been much better, but that is beyond the scope of
this report.

How can we reconcile the apparent agreement between traps and
independent measurements at HOT and an apparent c. 3-fold disagreement at
BATS? One suggestion is to conduct a 4-D-scale carbon and $^{234}$Th calibration to
verify the carbon and $^{234}$Th budgets. If done at BATS, would this be a
calibration of the trap methodology or a calibration of the carbon dynamics
around the BATS region? $^{234}$Th measurements have been made only recently
around HOT because the scavenging of $^{234}$Th is so low in oligotrophic regions
that the errors are large for this calculation and the data are not yet fully
analysed. K. Buesseler generally finds enough scavenging at BATS to make
these measurements, although there are times when there is no disequilibrium,
which means the predicted flux is zero.

What, then, is the calibration standard? Is it necessary to measure $^{234}$Th
depletion every time a trap measurement is made in the upper 200 m to
determine whether it is accurate? If we conduct a 4-D-scale trap—$^{234}$Th
experiment at a simple site, does that guarantee that similar trap measurements conducted elsewhere can use the same correction factor or scheme? Or do we take the hydrodynamics viewpoint and determine the conditions (especially velocity past the trap) under which traps collect particles without bias and then say that traps can be used under those conditions but that if the hydrodynamic conditions are not met the data must be discarded? There are strong proponents of both approaches.

We can make recommendations for JGOFS, but what is the penalty for non-compliance? What about all the trap measurements made outside JGOFS? They probably constitute the majority of trap measurements both now and in the future. What advice and legacy do we leave? Most people who use traps do not have the resources to measure either $^{234}\text{Th}$ or currents.

Before NASA sends an instrument into space (except for the Hubble space telescope), it is tested for responses in all conditions it might experience. Many calibration and comparison experiments have been made with sediment traps in both the laboratory and the field, but few calibration measurements have been made in the upper 200 m of the water column. The only calibration technique that has been suggested for calibrating traps on short time scales in this region is $^{230}\text{Th}$. Therefore, a 4-D $^{234}\text{Th}$ calibration of traps should be made to answer the question of trap efficiency, and there should be an oversight committee to ensure that all parameters are sufficiently characterised and measured. Such a study would also have to include measurements of vertical migrant and DOM transport.

Despite the concern about fluxes measured with floating sediment traps, Baines et al. (1994) have demonstrated a correlation between integrated chlorophyll concentration and carbon flux when a wide range of values are measured. Similarly, B. G. Mitchell et al. (in preparation) have shown a correlation between ocean colour plus surface temperature and particle flux when measured over the global range of ocean colour. Although there is significant scatter in the data and the precision is not known, it provides encouragement that it is possible to develop even better algorithms to make truly global calculations for the Joint Global Ocean Flux Study by using floating sediment traps.

**Major recommendations for trap sampling in surface waters**

1. Design and conduct a trap–$^{234}\text{Th}$ calibration experiment in the highest-productivity, lowest-energy regime that is practicable. There should be community input to the design of such an experiment even if only one or more groups conduct the work. The C: $^{234}\text{Th}$ ratio and $^{234}\text{Th}$
cycling between sinking and non-sinking particle pools is one of the crucial points of such an experiment. Migrant fluxes should also be measured simultaneously.

2. Pending the outcome of the above experiment, measure the $^{234}$Th deficiency during trap studies.

3. Make more experiments of the type of Baker et al. (1988) where the fluxes of moored traps are compared with fluxes in floating traps to test for hydrodynamic effects.

4. Develop and test neutrally buoyant traps.

5. Construct floating arrays to minimise the flow past traps, and measure the velocity past traps during deployment.

6. Decouple the trap from surface wave motion.

7. Measure flux at a single depth per array. Measurements at multiple depths are always desirable, but we must consider the importance of one measurement in which we have confidence compared with several numbers that might be compromised because of velocity effects.

8. Deploy traps with just 5 practical salinity units excess brine only in the bottom of the trap. Make the necessary tests to convert the BATS–HOT trap protocols to add brine only to a height of one trap diameter.

9. Carefully remove swimmers from samples.

10. Put the JGOFS protocols on the World Wide Web so they can be accessed easily.

11. Fully report methods and errors in all publications.

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